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AN AUTOMATIC SEISMIC DETECTION ALGORITHM.

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TECHNICAL REPORT NO. 7

VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

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Prepared by
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AFTAC Project No. VELA T/5705/B/ETR
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Frequency wavenumber detectors are designed and evaluated, and the feasibility of implementing the detectors on the Korean Station Processor is investigated. There was no significant difference between Fisher and conventional power detector performance at the same alarm rate, but both were improved with the use of the quality control algorithm and the prefilter. Azimuthal resolution was poor for all detectors, but the detectors were able to pick arrival times satisfactorily. One frequency-wavenumber detector consistently performed better than the others, and it was concluded that this type of detector offers no advantage over the wideband detectors. It was also found that either the Fisher or conventional power detector could be installed at the Korean Seismic Research Station (KSRS).



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ABSTRACT

Fisher and conventional power automatic seismic signal detectors, utilizing threshold adjustment to realize a constant alarm rate, are developed and evaluated on Korean Short-Period Array Data. Detector performance is measured at different alarm rates and integration gate lengths, both with and without a non-causal quality control algorithm and a prefilter. The detectors ability to pick arrival times and event azimuths is analyzed. Frequency wavenumber detectors are designed and evaluated, and the feasibility of implementing the detectors on the Korean Station Processor is investigated. There was no significant difference between Fisher and conventional power detector performance at the same alarm rate, but both were improved with the use of the quality control algorithm and the prefilter. Azimuthal resolution was poor for all detectors, but the detectors were able to pick arrival times satisfactorily. One frequency-wavenumber detector consistently performed better than the others, and it was concluded that this type of detector offers no advantage over the wideband detectors. It was also found that either the Fisher or conventional power detector could be installed at the Korean Seismic Research Station (KSRS).

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SECTION I

INTRODUCTION

This report presents results of a study of two automatic seismic signal detectors, the Fisher detector and the conventional power detector (Lane, 1973). This report is concerned with their response to short-period data at the Korean Seismic Research Station (KSRS), when they are constrained to have a constant average alarm rate. It is also the purpose of this report to determine if either detector is significantly superior to the other.

A total of 172 events from Eurasia and the South Pacific were processed by the detectors and the results were used to find a 50 percent probability of detection level by a maximum likelihood estimation procedure (Lane, 1974). The detectors' ability to pick event azimuth and arrival time was also analyzed. In Section IV, four frequency-wave number detectors were designed and compared with the wideband Fisher and conventional power detectors. In Section V the feasibility of installing the best detector at KSRS is discussed.

SECTION II

PREVIOUS RESULTS AND DETECTOR DESIGN

Two types of detectors, the conventional power detector and the Fisher detector, were compared. The conventional power detector output is the ratio of short term average beam power to the long term average power, while the Fisher detector output measures the coherent beam power divided by the incoherent beam power, averaged over some integration time period (Lane, 1974). In each case the output of the detectors, after normalization, is a measure of the signal-to-noise ratio (SNR).

A. PREVIOUS RESULTS

Previous studies of the Fisher and conventional power detectors, as implemented for the Korean Seismic Research Station (KSRS), showed that the false alarm rate was highly variable from day to day if a fixed threshold was used. At some thresholds, temporal variations as large as a factor of 20 were observed. Consequently such a detector will be far from optimum. On quiet days it will have few alarms, but will miss small events, while on noisy days it will be swamped with false alarms. To overcome this problem a detector with a constant alarm rate was developed.

B. DETECTOR DESIGN

This detector finds the threshold which yields the desired alarm rate by calculating the frequency of occurrence of each value of the detector's output, which is quantized in 0.1 dB increments. This is done by forming a

histogram whose intervals are labeled with the quantized values of the detector output. These intervals are referred to as bins. The bin contents are the number of times that the detector output has achieved that value or higher during some time interval.

At each time point the current histogram contents are multiplied by a factor of the form $1 - \Delta t/T$, where Δt is the sample time and T is the averaging time. Then the histograms are updated by adding a count equal to $\Delta t/T$ to all bins with labels less than the output of the detector. Consequently the contents of successive bins decrease or remain the same as their labels' increase. The contents of each bin, suitably scaled, represents the rate at which the detector has achieved that level, or higher, averaged over an interval on the order of T .

A separate histogram is kept for each detector, but outputs for every azimuth are included in the same histogram. In order to keep the alarm rate constant, the detector searches the contents of the bins for that number which corresponds to the desired alarm rate, and sets the threshold at the label of that bin.

At the beginning of computation, the histogram contents are all zero, so a certain "warm-up" time is required for them to come to their steady-state values. Sample calculations have shown that after about $2T$ the histogram values are such that the calculated threshold varies only slightly with time. Examples of such calculations are shown in Figure II-1, where the threshold calculated from seismic noise for alarm rates of 2, 5, 10, and 15 per hour are shown as a function of time, measured in units of T , beginning at processing initialization. The values of T used were 45, 18, 9, and 6 minutes. These values are 1.5 times the inverse of their respective alarm rate, and produced a combination of a rapid approach to equilibrium and good stability. The difference in threshold values for the largest and smallest alarm rate is about 4 dB. This implies an increase in detection capability of approximately $0.2m_p$ units for the higher alarm rate.

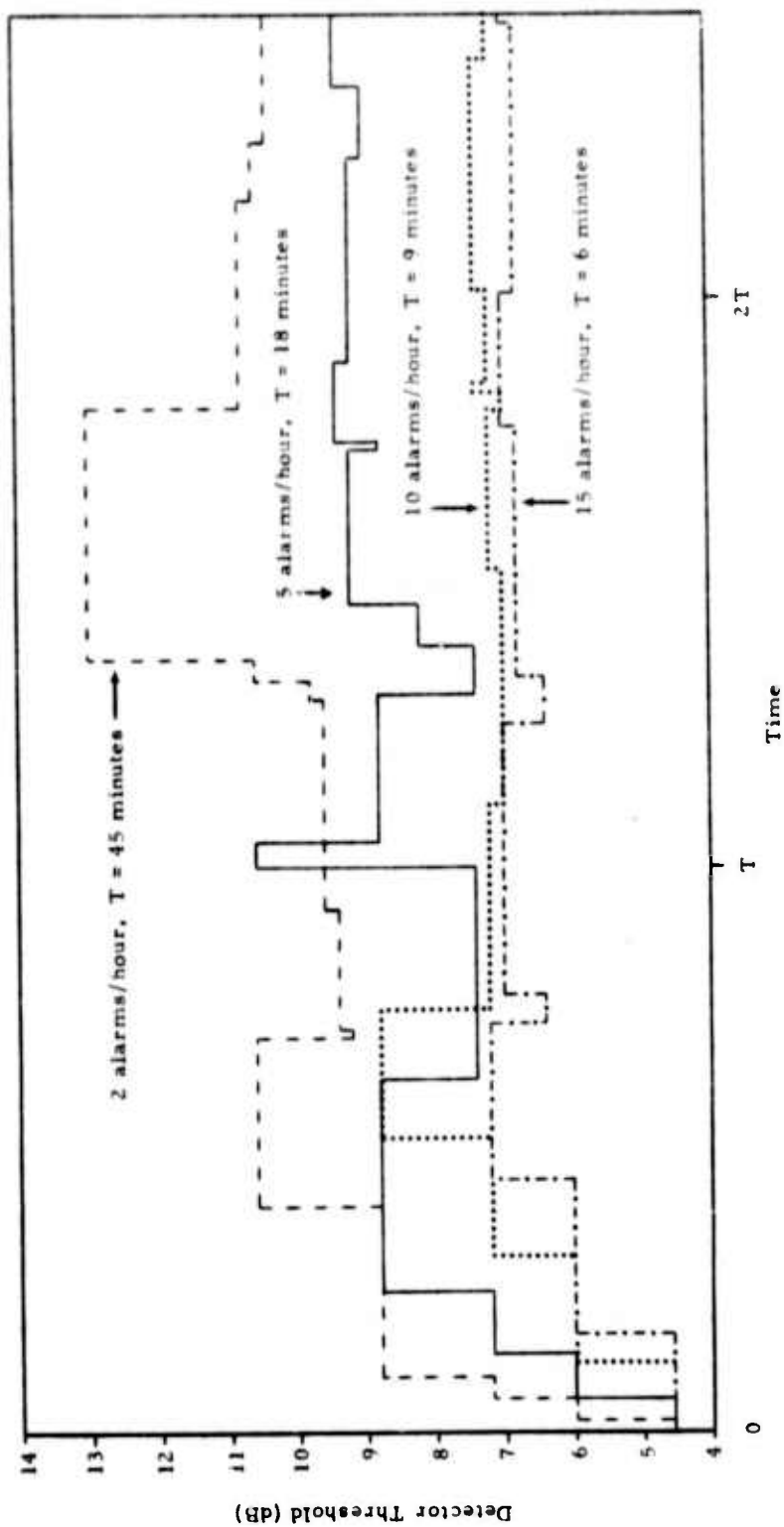


FIGURE II-1
DETECTION THRESHOLD VERSUS TIME

Table II-1 gives experimentally determined alarm rates found by counting the number of claimed detections generated in a four hour noise sample after a two hour warm-up period. The agreement with the expected values is quite satisfactory.

After a detection is claimed, no more detections are allowed for a certain "dead time", set at one minute in this study, in order to reduce the number of multiple detections due to the codas of large events. During this time the histograms are not updated. Since small events will be detected at high alarm rates but not at low ones, a separate histogram must be kept for each alarm rate to account for the different times during which each detector is not operating.

A prefilter was applied to each channel separately before any beamforming was performed. Its gain was essentially unity from 0.8 Hz to 3.2 Hz, and its response was -3dB at 0.5 Hz and 3.5 Hz. These values were suggested by experience gained by preliminary evaluation of KSRS (Prahl et al., 1975).

A non-causal quality control routine was incorporated into the detector in order to remove the influence of spikes and widely variant noise powers in the data. This algorithm calculates the individual channel powers, averaged over 2 seconds, and ranks them at each time point. Each channel whose power was either larger or smaller than the median by a factor of 6 was discarded for a period of 8 seconds, when it was again checked. The algorithm was non-causal in the sense that channels were discarded 4 seconds before they entered the calculation of the detector outputs. Therefore a varying channel power, due to increasing or decreasing noise, did not influence the detector. On tests with noisy samples, where some channel powers varied erratically with time, this algorithm successfully turned off those channels without allowing them to influence the noise power calculations.

TABLE II-1
EXPERIMENTALLY DETERMINED
ALARM RATE

Desired Alarm Rate	Average Alarm Rate
<u>15 Alarms</u> Hour	<u>13.8 Alarms</u> Hour
<u>10 Alarms</u> Hour	<u>9.0 Alarms</u> Hour
<u>5 Alarms</u> Hour	<u>4.5 Alarms</u> Hour
<u>2 Alarms</u> Hour	<u>2.5 Alarms</u> Hour

The previous study indicated that there probably was no improvement in detection capability when the short term averaging interval for the conventional detector, and the integration time, in the case of the Fisher detector, varied from 0.8 to 6.4 seconds, but that additional investigation was required. To accomplish this, values of 0.8 and 3.2 seconds were used for the time gates here.

In this study beams were formed at azimuths, measured clockwise from North, of 30, 150, 240, 270, 300, 330, and 360 degrees. A plane wave velocity of 15.1 km/sec was used, corresponding to an epicentral distance of 50 degrees. These choices span the entire region of interest.

SECTION III

ANALYSIS OF THE DATA

The purpose of this section is to present the detection capability of the automatic detectors described in Section II determined from a large data sample. A maximum likelihood detection curve was calculated for each detector. A test of the detectors' ability to pick the arrival time of an event is also discussed.

A. DATA BASE

Data are recorded at KSRS on library tapes of approximately eight hours duration. The short-period data are recorded for 19 channels at a rate of 20 samples per second, for the vertical component only, but were decimated to 10 samples per second for processing here. Data are available continuously for the period beginning 1 November 1974, and ending 30 November 1974. From this time period 172 events reported by the Earthquake Data Report (EDR) and LASA bulletins were selected for processing. These events were chosen because their epicentral distance from KSRS was less than 100 degrees and their azimuths lay within 30 degrees of the look directions used here.

All events with no reported m_b value were excluded from the data base. In addition, the reported m_b values were recalculated using only magnitude estimates from stations located at teleseismic distances from the event since stations that are closer than 20 degrees tend to report m_b estimates that are biased (Bungum and Husebye, 1974). A histogram of the number of events versus magnitude is shown in Figure III-1. A list of the distribution of events by region is shown in Table III-1.

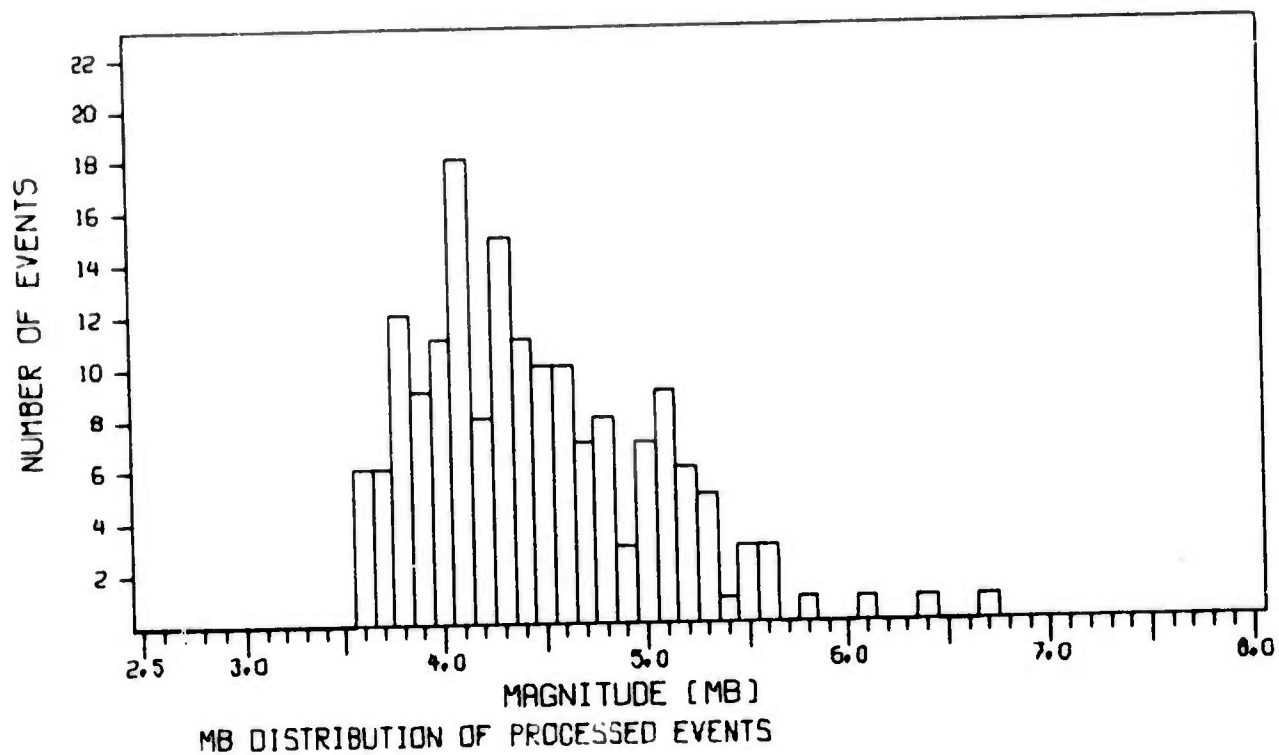


FIGURE III-1
DISTRIBUTION OF EVENTS BY MAGNITUDE

TABLE III-1
DISTRIBUTION OF EVENTS BY REGION

Region	Number of Events
Kuriles, Kamchatka, Alaska	54
Pacific Ocean	57
Mediterranean	21
China and Eastern Russia	10
Western Russia	14
Miscellaneous	16
Total Number of Events	172

The quality of the data was fair. There were several instances in which the data contained spikes but these were not excluded from the data base because the quality control algorithm incorporated into the detectors eliminates their effects. The data occasionally contained instrument calibrations that were not reported in the station logs or indicated by the library tape channel-use status bits. These calibrations never occurred on more than half the channels simultaneously, so the quality control algorithm was able to remove their effects. When these data were processed by the detectors without quality control, continuous alarms occurred on the conventional detector, while the Fisher detector output was driven to zero.

B. EXPERIMENTAL PROCEDURE

To determine if an event was detected, the arrival time was calculated using a standard travel time table with a depth correction factor. If there was a detection in the interval delimited by the calculated arrival time plus/minus 15 seconds it was assumed to be due to the event.

Associated with any interval is the probability that the detector output will exceed the threshold due to the presence of noise. For high alarm rates this is approximately equal to the alarm probability, which is set by the detector design at:

$$\begin{aligned} & (\text{Fractional interval of hour searched for detection}) \cdot (\text{Alarm} \\ & \text{rate per hour}) \cdot (\text{Number of beams allowed for} \\ & \text{detection}) / (\text{Total number of beams}). \end{aligned} \quad (\text{III-1})$$

This false alarm probability was incorporated into the maximum likelihood estimation procedure as described by Lane (1974).

To insure that a stable detection threshold was attained by the detectors, a warm-up period equal to 36 minutes of data was used during processing. This is greater than or equal to twice the time constants defined in Section II for all alarm rates except 2 alarms/hour. Accordingly the detection

threshold, and therefore the detection capability, at 2 alarms/hour is probably somewhat lower than it would actually be if a detector with this alarm rate was installed at KSRS.

In order to determine the best detector, we first constructed a histogram of detections and non-detections of events at each m_b level for each detector. Then, using each histogram, a maximum likelihood detectability curve was calculated. The detector with the best detectability curve was chosen as the optimum detector.

Given the false alarm probability and the histogram of detections and non-detections, we can calculate the maximum likelihood detectability curve (Ringdal, 1974; and Lane, 1974). This algorithm assumes that the detectability curve is a cumulative Gaussian distribution function of the form:

$$P(\text{Detect } m) = (1 - P_{fa}) \int_{-\infty}^m (2\pi s^2)^{-1/2} \exp \left\{ -(m' - m_o)^2 / 2s^2 \right\} dm' + P_{fa} \quad (\text{III-2})$$

where P is the probability of detection at an m_b level equal to m , m_o is the 50 percent detection threshold, s is a standard deviation, and P_{fa} is the probability of a false alarm. The variables m_o and s are determined from the data by the maximum likelihood procedure. Figure III-2 illustrates the results of these calculations for the Fisher detector at 15 alarms/hour and a 0.8 second time gate. In the figure the value of the curve at $m_b = 2.5$ corresponds to P_{fa} , sigma represents s , and MB50 is m_o .

The 50 percent detection level and 90 percent detection level found from the detection curve in Figure III-2 are somewhat less than the MB50 and MB90 shown to the right of the figure, because of the presence of false detections due to noise. An attempt will be made to associate these noise detections with detections claimed by another station. Shoup and Sax (1974) have shown that the probability of false associations due to this kind of false alarm is very low. Consequently most of them will be rejected, and the detection levels for true events will rise to the value listed as MB50 and MB90.

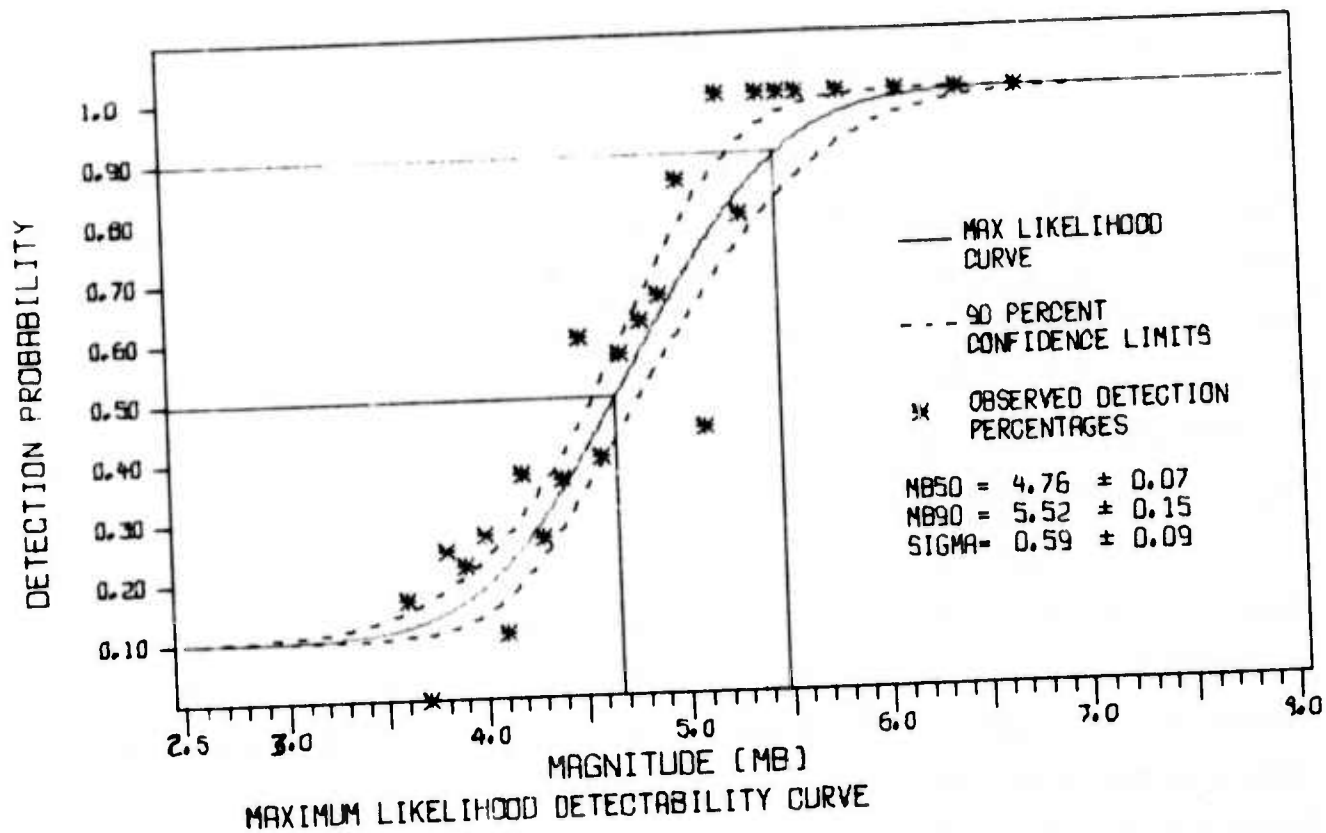
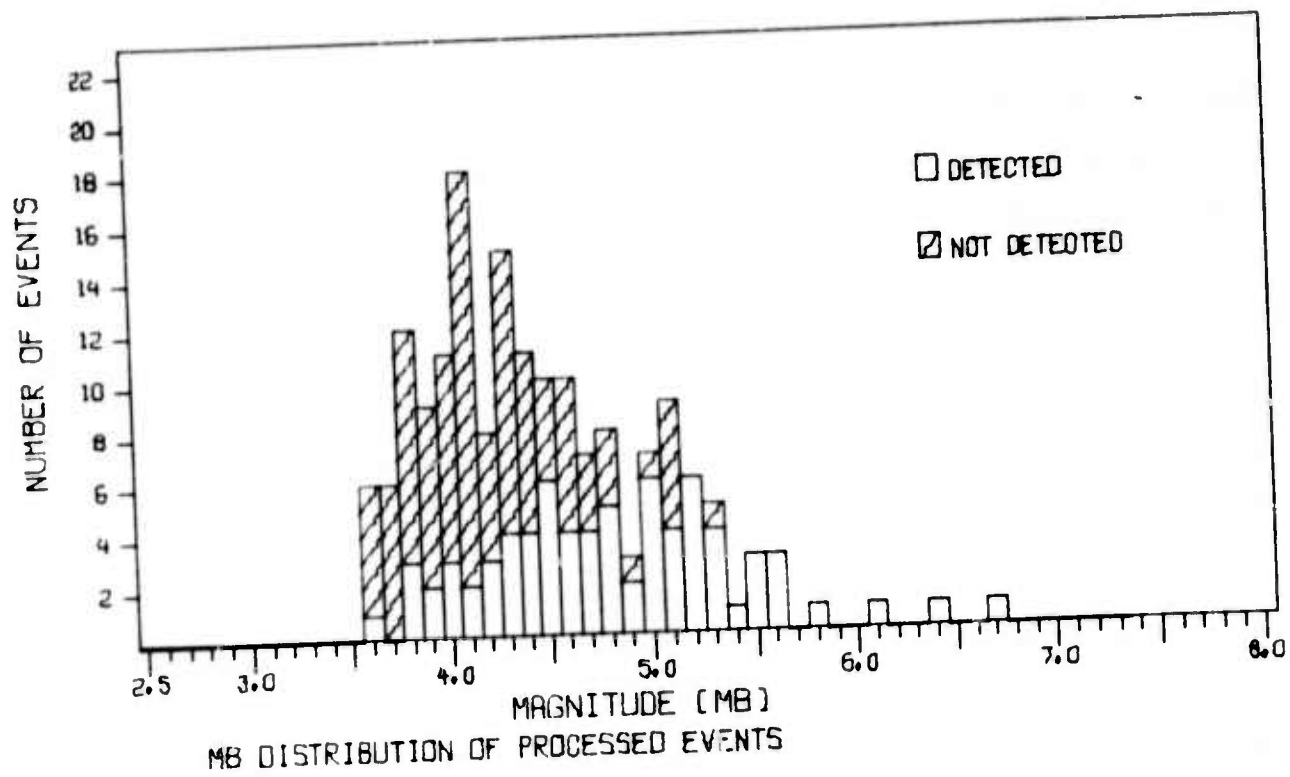


FIGURE III-2

EXAMPLE OF THE MAXIMUM LIKELIHOOD ESTIMATION TECHNIQUE

For purposes of a comparison, a sample of 92 events were processed with the detectors without quality controls. In addition, detectability curves were calculated for the detectors using quality controls both with and without the constraint that the detection occur on a beam within 30 degrees of the event azimuth. The location of an event can be determined if four arrival times at different stations are accurately known even without azimuthal information. Therefore, any improvement in detection capability of the detectors without azimuthal constraints would be important.

C. DETECTION CAPABILITY OF THE VARIOUS DETECTORS

The results of this study show that there is very little difference between the Fisher and conventional detectors' detection capability at a constant false alarm rate, regardless of the time gate used. This is consistent with the results reported by Lane (1974). However, there is a considerable decrease in detection capability when azimuthal constraints are applied or the quality controls are removed.

Table III-2 presents the maximum likelihood detectability parameters when the detectors with quality controls were used. The meaning of sigma is the same as described in Subsection III-B, while $m_b 50$ and $m_b 90$ are equivalent to MB50 and MB90 shown in Figure III-2 and described above. The 67% confidence limits on the detection parameters are also shown. The value of $m_b 50$ is the most reliable (Ringdal, 1974), and therefore is used as the primary measure of detector performance.

In general, the $m_b 50$ level increases as the number of alarms per hour decreases. With the exception of the conventional detector with a 3.2 second time gate, there is a significant difference between the $m_b 50$ level at 15 alarms/hour and an alarm rate of 2 per hour. This difference is about 0.1 magnitude units, which is consistent with the predictions of Section II and Subsection III-B. The $m_b 90$ level has a minimum at 10 alarms/hour but this is not

TABLE III-2
DETECTION PARAMETERS FOR DETECTORS WITHOUT
AZIMUTHAL CONSTRAINTS AND WITH QUALITY CONTROLS

Alarm Rate	Detection Parameters (m_b)	Fisher Detector	Conventional Detector	Fisher Detector	Conventional Detector
		0.8 Second Gate		3.2 Second Gate	
15 Alarms Hour	m_b 50	4.76 \pm 0.07	4.78 \pm 0.07	4.69 \pm 0.07	4.90 \pm 0.06
	m_b 90	5.52 \pm 0.16	5.48 \pm 0.14	5.42 \pm 0.15	5.43 \pm 0.11
	Sigma	0.59 \pm 0.09	0.55 \pm 0.08	0.56 \pm 0.08	0.41 \pm 0.06
10 Alarms Hour	m_b 50	4.78 \pm 0.06	4.78 \pm 0.06	4.70 \pm 0.07	4.83 \pm 0.06
	m_b 90	5.41 \pm 0.13	5.41 \pm 0.13	5.40 \pm 0.14	5.36 \pm 0.11
	Sigma	0.49 \pm 0.07	0.50 \pm 0.07	0.55 \pm 0.08	0.41 \pm 0.06
5 Alarms Hour	m_b 50	4.87 \pm 0.07	4.80 \pm 0.07	4.76 \pm 0.06	4.86 \pm 0.06
	m_b 90	5.54 \pm 0.14	5.43 \pm 0.13	5.41 \pm 0.13	5.43 \pm 0.12
	Sigma	0.52 \pm 0.07	0.49 \pm 0.07	0.50 \pm 0.07	0.44 \pm 0.06
2 Alarms Hour	m_b 50	4.88 \pm 0.06	4.86 \pm 0.07	4.86 \pm 0.07	4.92 \pm 0.07
	m_b 90	5.45 \pm 0.12	5.47 \pm 0.13	5.53 \pm 0.14	5.59 \pm 0.15
	Sigma	0.44 \pm 0.06	0.47 \pm 0.07	0.52 \pm 0.07	0.51 \pm 0.07

a significant improvement. Over the entire range of magnitudes in the data base the improvement in detection parameters at the highest alarm rate represents about 20 additional detected events out of 172.

At all alarm rates, the Fisher detector with a 3.2 second time gate yields the lowest $m_b 50$ value. However, the difference in $m_b 50$ values for this detector and others is usually less than the confidence limit and therefore is probably not significant. For this detector the $m_b 50$ and $m_b 90$ values are 4.7 and 5.4, respectively.

The value of the $m_b 50$ parameter for the detectors employing prefiltering and quality controls is 0.5 to 0.8 magnitude units less than the value of the same parameter when the detectors with no prefiltering and quality controls were used, while the $m_b 90$ parameter is 0.4 to 1.1 magnitude units better. Table III-3 shows all the detection parameters for the detectors without quality controls. The range of $m_b 50$ in this table is 5.2 to 5.5 and the range of $m_b 90$ is 5.8 to 6.5.

The detection parameters calculated from an analysts claimed detections on a data base containing 38 events were $m_b 50 = 4.5$ and $m_b 90 = 4.9$ (Prahl et al., 1975). This is an improvement of 0.2 and 0.5 over the values found using the best automatic detector. The larger difference in $m_b 90$ is due to the smaller value of sigma found by Prahl. However, his small data base makes his results less reliable.

Table III-4 lists the detection parameters for the Fisher and conventional power detectors employing quality controls when detections were constrained to appear on a beam within 30 degrees of the signal azimuth. The important feature of this table is that there is no definite trend for $m_b 50$ or $m_b 90$ to increase as the alarm rate decreases, as expected from the variation of the detection threshold, and found previously in the study without azimuthal constraints. The result is presumably due to the combination of two factors - the influence of noise and the broad beamwidth at the small Korean array.

TABLE III-3
DETECTION PARAMETERS FOR DETECTORS WITHOUT
AZIMUTHAL CONSTRAINTS AND QUALITY CONTROLS

Alarm Rate	Detection Parameter(m_b)	Fisher Detector	Conventional Detector	Fisher Detector	Conventional Detector
		0.8 Second Gate		3.2 Second Gate	
15 Alarms Hour	m_b 50	5.27 \pm 0.19	5.47 \pm 0.23	5.26 \pm 0.12	5.33 \pm 0.18
	m_b 90	6.26 \pm 0.39	6.51 \pm 0.45	5.79 \pm 0.22	6.24 \pm 0.37
	Sigma	0.77 \pm 0.19	0.80 \pm 0.21	0.42 \pm 0.10	0.70 \pm 0.17
10 Alarms Hour	m_b 50	5.21 \pm 0.16	5.42 \pm 0.22	5.37 \pm 0.13	5.44 \pm 0.22
	m_b 90	6.05 \pm 0.32	6.46 \pm 0.45	5.89 \pm 0.25	6.46 \pm 0.46
	Sigma	0.65 \pm 0.15	0.80 \pm 0.20	0.41 \pm 0.11	0.80 \pm 0.20
5 Alarms Hour	m_b 50	5.32 \pm 0.17	5.33 \pm 0.20	5.34 \pm 0.13	5.42 \pm 0.22
	m_b 90	6.14 \pm 0.34	6.36 \pm 0.43	5.87 \pm 0.24	6.46 \pm 0.45
	Sigma	0.64 \pm 0.15	0.80 \pm 0.20	0.41 \pm 0.11	0.80 \pm 0.20
2 Alarms Hour	m_b 50	5.52 \pm 0.20	5.38 \pm 0.21	5.37 \pm 0.14	5.44 \pm 0.21
	m_b 90	6.33 \pm 0.39	6.41 \pm 0.44	5.95 \pm 0.27	6.40 \pm 0.43
	Sigma	0.63 \pm 0.16	0.80 \pm 0.20	0.45 \pm 0.12	0.75 \pm 0.19

TABLE III-4
DETECTION PARAMETERS FOR DETECTORS WITH
AZIMUTHAL CONSTRAINTS AND QUALITY CONTROLS

Alarm Rate	Detection Parameters (m_b)	Fisher Detector	Conventional Detector	Fisher Detector	Conventional Detector
		0.8 Second Gate		3.2 Second Gate	
15 Alarms Hour	m_b 50	5.11 \pm 0.12	5.04 \pm 0.10	5.00 \pm 0.11	5.20 \pm 0.13
	m_b 90	6.15 \pm 0.28	5.91 \pm 0.21	6.03 \pm 0.26	6.23 \pm 0.29
	Sigma	0.80 \pm 0.14	0.67 \pm 0.11	0.80 \pm 0.14	0.80 \pm 0.14
10 Alarms Hour	m_b 50	5.04 \pm 0.10	5.08 \pm 0.10	5.00 \pm 0.11	5.17 \pm 0.13
	m_b 90	5.90 \pm 0.21	5.96 \pm 0.23	6.03 \pm 0.26	6.20 \pm 0.29
	Sigma	0.67 \pm 0.11	0.69 \pm 0.11	0.80 \pm 0.14	0.80 \pm 0.14
5 Alarms Hour	m_b 50	5.05 \pm 0.09	5.05 \pm 0.09	5.01 \pm 0.10	5.24 \pm 0.14
	m_b 90	5.78 \pm 0.18	5.85 \pm 0.19	5.85 \pm 0.20	6.27 \pm 0.30
	Sigma	0.56 \pm 0.09	0.61 \pm 0.10	0.65 \pm 0.10	0.80 \pm 0.14
2 Alarms Hour	m_b 50	5.02 \pm 0.08	5.08 \pm 0.10	5.06 \pm 0.10	5.30 \pm 0.14
	m_b 90	5.67 \pm 0.15	5.88 \pm 0.20	5.95 \pm 0.22	6.33 \pm 0.31
	Sigma	0.50 \pm 0.07	0.62 \pm 0.10	0.69 \pm 0.11	0.80 \pm 0.15

Calculation of the array response showed that for the beam-forming velocity used here, the 6 dB full beamwidth was about 120 degrees at 1.0 Hz, the frequency of maximum signal energy. Consequently even a small amount of distortion may cause the event to be detected on a beam far from the azimuth of the signal. Because detectors with low thresholds detect at a lower signal-to-noise ratio, and therefore sooner than those with high thresholds, more noise energy appears in the integration gate. This noise causes enough distortion to produce a detection on an incorrect beam.

Detectors with higher alarm rates and hence lower thresholds had a broader distribution of detections with azimuthal separation from the great circle path, supporting the arguments above. These results suggest that no detection scheme at KSRS will yield good azimuthal resolution.

D. ARRIVAL TIME STUDY

Eleven events were selected for this study. In each case an analyst was able to detect the event and determine its arrival time from a plot of beamed data (Prahl et al., 1975). These events were also detected by the automatic signal detectors with quality controls as described in Section II. The events ranged in magnitude from 4.4 to 5.4.

The detector arrival times were taken to be the times at which the detector output first rose above the threshold. Arrival times determined by the detection algorithm were later than the analyst determined time for all but 2 events. Table III-5 gives the mean difference between these times and the standard deviation of this time for each type of detector and integration time at an alarm rate of 15 per hour. A positive time difference indicates that the automatic detector found the event after the analyst did.

From the table it is readily seen that there is no difference between detectors with the same integration time. The table also shows that the longer gate yields a better estimate of the arrival time. This is because

TABLE III-5
ARRIVAL TIME ERRORS FOR THE DETECTORS
AT 15 ALARMS/HOUR

Type of Detector	Gate Length	Mean Time Difference (Seconds)	Standard Deviation (Seconds)	Range (Seconds)
Fisher Detector	0.8 Seconds	2.8	2.1	-0.5 — 7.0
	3.2 Seconds	1.5	1.7	-0.9 — 4.6
Conventional Power Detector	0.8 Seconds	2.7	2.3	0.1 — 8.6
	3.2 Seconds	1.5	1.7	-0.9 — 4.6

the detectors with longer time gates have lower thresholds, since they reduce the variance in the noise power by smoothing over a longer time. However, the actual long term noise power is the same on the average for detectors with all gate lengths, meaning that a smaller average signal power is required to reach the threshold for the longer time gate. This smaller power is achieved earlier by the longer gate because the signal enters it earlier. Similar arguments can be made with respect to the Fisher detector.

A more important measure of detector performance, with respect to arrival time, is the standard deviation, since the mean error can always be removed. Then the detectors with the smaller standard deviation will more likely be correct. These are the detectors with the 3.2 second gates. The maximum difference between standard deviations for different integration times is 0.6 seconds, less than the 0.8 second quantization unit used here. If this difference is significant, it is presumably due to the greater smoothing of the signal over the longer integration gate, yielding more regular behavior.

At other alarm rates the time differences and standard deviations increased monotonically. Less consistency was observed between detectors at 0.8 second integration time at lower alarm rates. In particular the mean time difference and its standard deviation for the Fisher detector at 0.8 seconds increased to 3.9 and 2.5 seconds, respectively, although the conventional detector's performance did not change significantly. Performance for the 3.2 second gate detectors was unchanged over the range of alarm rates for the small data sample used here. This suggests that the shorter time gates may yield less stable arrival time estimates. In the absence of a larger data sample, we can only conclude that the average mean time difference between machine and analyst picked arrival times, and the standard deviation, are acceptably small.

SECTION IV

FREQUENCY-WAVENUMBER DETECTORS

Four frequency-wavenumber (f-k) detectors were designed and implemented for analysis. The four detectors combined two prefilters and two beams formed at different wave velocities. The peaks of the prefilter responses were at 1.0 Hz and 1.8 Hz, centered in a passband of about 0.4 Hz, defined here as the interval between the points where the prefilter response is 3 dB less than its 0 dB maximum. Beams were formed from each set of filtered channel outputs using plane wave velocities of 10 km/second and 15 km/second. These velocities correspond approximately to epicentral distances of 20 and 50 degrees, respectively. The beam look directions used here were 150, 240, 270, and 300 degrees. All other detector parameters were the same as described in Section II.

Twenty-nine events were selected from the region spanned by these beams and were processed with the f-k detectors and the wideband detectors used in Section III. The f-k detectors outputs were measured to determine the maximum and then compared to the wideband detectors outputs. For each event the detection threshold was about the same for all detectors, so that the detector with the greatest output would be the best. This analysis showed that there probably would be no advantage to implementing an f-k detector instead of a wideband detector since in most cases the same f-k detector had the greatest output. A second result was that the prefilter for the wideband detector should have a low end cutoff frequency slightly higher than 0.5 Hz as used in Section III.

In the set of 29 events, seven had an epicentral distance less than 30 degrees and 22 events had an epicentral distance of more than 40 degrees.

For the 7 near events, it would be expected that the f-k detector with a pre-filter centered at 1.8 Hz and a plane wave velocity of 10 km/second would yield the maximum output since the energy of close events is usually concentrated at higher frequencies. However, for these events, no one f-k detector was consistently superior to the others. Of the 22 events located at a distance greater than 40 degrees the f-k detector with a prefilter at 1.0 Hz and a plane wave velocity of 15 km/second had the maximum output in 15 cases as expected. Over the entire set of events this detector had the highest output in 18 instances. These facts lead us to believe that there would be no advantage to implementing the f-k detector.

It was also noted that when the 1.0 Hz, 15 km/second f-k detector yielded the maximum output, it was greater than the wideband detector output for 15 of 18 events, but when any one of the other f-k detectors responded best, its output was about the same as the wideband detector output for that event. Therefore, we conclude that the wideband detector should be designed with a low end cutoff frequency of about 0.8 Hz and a 15 km/second beam velocity, with the high end cutoff frequency not being too critical.

SECTION V

COST .. PERFORMANCE ANALYSIS

The purpose of this section is to study the feasibility of implementing on the station processor located at KSRS an automatic detector of the type discussed in the previous sections. It is also the intent of this section to determine any tradeoffs between detector design, and the computation time and computer memory available to implement the detector. Since there is no significant difference in detection capability between the detectors studied here, the choice of the optimum detector can be made on the basis of these constraints.

A. IMPLEMENTATION CONSTRAINTS

The station processor at KSRS consists primarily of a Texas Instruments 980-A minicomputer with an Advanced Array Transform Processor (AATP) (Texas Instruments, 1974). The AATP is a hardwired device, with significant computational advantages that enable the station processor to perform arithmetic operations on vectors in the same time required for normal scalar operations. Therefore, algorithms such as beamforming and linear filtering can be computed very quickly.

The 980-A has 32 thousand (K) 16 bit words of memory. It requires two words to represent a floating point number. Of the total available memory, 27K words are used, on the average, for existing functions, leaving approximately 5K words to implement the detector (Kunkel, 1975). The exact amount of available core depends on the configuration of the station processor; that is the number of beamsteers, multichannel filters, and adaptive filters that are performed. Typically, the time required to compute these

functions is 50 milliseconds (msec) per 0.1 second data sample. The precise execution time also depends upon the configuration.

Some functions that can now be performed by the station processor are required by the detector algorithm. These are beamsteering, quality control excluding the storage needed to make it non-causal, and beamsteer filtering and/or postfiltering. Since no filter outputs were recorded on the library tapes, it is assumed that this operation was not included when the available core and time was calculated above. Therefore, it is included in our estimate of the implementation requirements.

B. IMPLEMENTATION REQUIREMENTS

The automatic detectors examined here were developed on an IBM 360 model 44 computer. The primary portion of the detector software was coded in FORTRAN programming language, while most of the support routines were coded in ALC, which is the IBM assembler language. These support routines consisted of a driver program, card input program, tape control programs, a line printer output program, plus other routines that are not needed to implement the detector at KSRS. All of these programs, and the beamforming and quality control routines, which are already implemented at KSRS, were not included in the estimate of the time and core requirements here. Since only a crude estimate of the time requirement can be made, it is assumed that the execution time of a single instruction is the same for both the IBM 360/44 and the 980-A. Therefore the total reduction in execution time per sample point from the IBM 360/44 to the 980-A is proportional to the decrease in the number of instructions that are executed. On the average, this assumption is fairly accurate.

1. Core Requirements

Table V-1 describes the storage buffers and itemizes the core, in words, required to implement the Fisher and conventional power detector.

TABLE V-1
CORE REQUIREMENTS FOR BUFFERS AND INSTRUCTIONS
TO IMPLEMENT AN AUTOMATIC DETECTOR AT KSRs

Description of Item	Fisher Detector With 3.2 Second Gate (in words)	Conventional Power Detector With 3.2 Second Gate (in words)
Filter Coefficients	30	30
Filter Buffer	600	220
Bin Values	100	100
Bin Labels	100	100
Quality Control Buffer	760	760
Non-Causal Channel Status Counters	20	20
Beam Sum	30	30
Beam Square Sum	30	0
Beam Noise Powers	0	10
Miscellaneous	100	100
Subtotal	1770	1370
Doubled Because Floating Point Variables	3540	2740
Instructions	1400	1400
Total	4940	4140

The values listed in the table are for the detectors with a 3.2 second integration gate with the output sampled every 0.8 seconds. For the detectors with a 0.8 second gate the core requirements would decrease no more than 50 words. All values in the table are rounded off to the nearest 10 words.

The first item in the table is the core required for the filter coefficients. A 31 point convolution filter was used here and the filter buffer required for the conventional detector is 220 words. This is one word per filter point per beam or $31 \times 7 \cong 220$. On the other hand, the Fisher detector requires a larger filter buffer because the filtering must be done prior to beamforming. This is because the Fisher detector equation is not linear, but includes the sum of the squares of the filtered, beamsteered channel traces. The total buffer here consists of one word per filter point per channel which is equal to $31 \times 19 \cong 600$ words. It is possible to reduce the storage requirement for the filter by designing a filter that uses both previous inputs and outputs. However, only a slight increase in execution time would result because it would not make as efficient use of the AATP.

One hundred histogram bins were used for both detectors to retain a constant alarm rate. Therefore, 100 words are needed for the bin values and 100 words for the bin labels. If the bin labels are uniformly separated, the core required for the labels can be reduced to less than 10 words.

The next item in the table is the extra storage needed to make the quality control algorithm non-causal. The total storage is directly proportional to the time lag between data acquisition and processing, 4 seconds in this case. Therefore the core requirement for this is (number of channels) \times (timelag, in seconds) \times (sample rate per second) which is $19 \times 4 \times 10 = 760$ words. To fill out the 8 second interval during which a channel was discarded, one status counter per channel was used for an additional 20 words. Both of these items are independent of the detector that is implemented.

The following three items are directly related to the detector equations. The total storage required for each of the beam sum and beam squared sum is equal to the ratio of the integration gate to the sample rate of the output, which is 4 for the detectors used here, multiplied by the number of beams, seven in this case. The core allocated for the beam noise power is one word per beam. The Fisher detector equation makes use of the beam sum and beam squared sum for a total of 60 words, while the conventional power detector uses the beam sum and the beam noise powers for a total of 40 words.

The last storage buffer is allocated for miscellaneous variables such as time constants and the false alarm rate. The total core for these is estimated to be 100 words for both detectors.

The total core for all of the buffers described above must be doubled because two words are required to represent a floating point number on the 980-A. This yields a total of 3540 words for the Fisher detector and 2740 words for the conventional power detector.

On the IBM 360/44, the code used to implement the detectors, excluding support routines occupied 2500 words of core. Of this total about 90%, 2200 words, were coded in FORTRAN. The program included code to test 4 detectors and 4 alarm rates. Since only one detector and one alarm rate would be implemented at KSRS, and since the detector would be coded in an assembler programming language, a very reasonable estimate is that the 2200 words now coded in FORTRAN could be reduced by a factor of two. This means that the total computer memory required for the instructions is 1400 words.

The final total is about 5.0K words to implement the Fisher detector and 4.2K words for the conventional power detector. Since the original constraint was 5K words, there would be no problem fitting the power detector into the available space, whereas the core required for the Fisher detector very nearly approaches the limit. It is our opinion that the estimates stated

above are at least exaggerated by 10%, so that either detector could be implemented in the available core.

2. Time Requirements

When the detector programs were executed on the IBM 360/44, the computation speed was approximately 0.6 real time. This is 60 msec. per 0.1 second data sample. There are three factors that would reduce the execution time. The first is the use of the AATP to perform the filter and beamforming operations. The second factor is that the actual number of steps to implement the detector will be cut in half. This is due to the fact that there will be only one alarm rate and detector, and the beamforming and quality control are already included in the station processor's functions. Finally, the support routines that performed input and output operations will no longer be used. Therefore, the actual time requirement should be less than 30 msec. per 0.1 second data sample, well within the constraint of 50 msec. per data sample. Since either detector could be implemented within the constraints, no tradeoffs between detector design and available core and time have to be made. In fact, it would very well be possible to implement both the Fisher and conventional power detectors at KSRS.

SECTION VI

CONCLUSIONS

This report has presented the design and evaluation of the Fisher and conventional power seismic event detectors utilizing automatic threshold adjustment to realize constant alarm rates on Korean short-period array data. Detector performance was evaluated both with and without a non-causal quality control algorithm and a prefilter. Different detector integration times and alarm rates were used for performance evaluation and the ability of the detectors to correctly resolve signal arrival times and azimuth was analyzed. Frequency wavenumber (f-k) detectors were designed and tested, and the feasibility of installing the best detector design on the Korean station processor was investigated.

A beam velocity of 1591 km/sec corresponding to a 50 degree epicentral distance, beams separated by 30 degrees that spanned the Eurasian region, and one beam looking toward the southwest Pacific Ocean, were used for all detectors. Integration gates were set at 0.8 and 3.2 seconds and alarm rates at 15, 10, 5, and 2 per hour. The prefilter passed signal energies that lay in the 0.5 to 3.2 Hz band.

The automatic threshold algorithm formed a histogram of number of alarms versus threshold averaged over a long interval. Then the detection threshold was set at the level where a pre-specified number of alarms occurred. A satisfactory constant alarm rate was obtained when tests were made on a 4 hour noise sample.

Each detector configuration employing quality controls and pre-filtering was used to process data covering 172 events reported by the Earthquake Data Report (EDR) and 92 events were processed by the same detectors

without quality controls or prefiltering. Only alarms occurring within 15 seconds of the arrival times calculated from standard travel time curves were considered to be true detections. From these results a histogram of detections and non-detections as a function of magnitude was constructed and a maximum likelihood procedure was used to derive a detection probability curve that assumes a Gaussian distribution of world-wide magnitudes for a given event. The primary criterion of detector performance was taken to be the magnitude at which the 50% probability of detection was measured from this curve.

It was found that detector performance at a fixed alarm rate was affected very little by the detector type and integration time. However, when the quality controls and prefiltering were omitted the detector performance was uniformly degraded by about 0.6 magnitude units from the 50% detection level equal to 4.8 that was determined from the detectors with quality controls and prefiltering. For various detector configurations the 50% detection level varied by 0.1 magnitude units.

A large portion of these events were detected on beams other than the signal azimuth. When detections were required to occur on a beam within 30 degrees of the great circle path to the event epicenter the 50% detection level rose to about 5.1, also with little variation between different detector configurations. The cause of the poor azimuthal resolution was due to the large beam width of the Korean short-period array. Therefore only a very small amount of noise in the integration gate could cause a detection to occur on the wrong beam. Since seismic events are located using only timing information, the performance of the Korean array may be satisfactory even without azimuthal constraints.

The arrival times picked by the automatic detectors were usually later than those found by an analyst for the small sample of events we used. The average timing error was less for those detectors with the longer integration gate, but the maximum average error was never greater than 3.0 seconds

in any case. A more important parameter is the standard deviation of the timing errors, since it is desired that they be minimized. The standard deviation was also less for the detectors with the 3.2 second integration gate, with the maximum for all detectors being 2.5 seconds.

Frequency wavenumber detectors were designed with wave velocities equal to 10 km/sec and 15 km/sec, corresponding to epicentral distances of 20 and 50 degrees respectively. Each was narrowband filtered at 1.0 Hz and 1.8 Hz and implemented for all detector configurations. For a sample of 30 events, it was found that the f-k detector with a 15 km/sec velocity and 1.0 Hz filter consistently outperformed the others. Therefore it was concluded that the f-k detector would probably have no advantage over the wideband detector, but that the wideband detector is close to optimum since it nearly approximates the best f-k detector. Only a slight change in the prefilter would make it optimum.

Since there is no significant difference in detection capability of the detectors examined here, the choice of the optimum detector can be made on the basis of computer core requirements and execution time. At the Korean station processor, there is about 5000 words of core available and approximately 50 milliseconds per 0.1 second datum point in which to implement the detector. It was estimated that the conventional detector would require about 4.2 thousand words to implement while the Fisher detector would require very nearly 5.0 thousand words. It was also estimated that with the use of the Advanced Array Transform Processor either detector would operate in 0.3 real time which is 30 milliseconds per datum point. This is well below the time available. It was concluded that no tradeoffs between computer costs and detector performance would have to be made for either detector.

SECTION VII

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